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**NON-STEADY FLOW-DIRECTION GENERATION AND MEASUREMENT**

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# NON-STEADY FLOW-DIRECTION GENERATION AND MEASUREMENT

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## ABSTRACT

A generator of non-steady airflow direction has been developed to test the ability of a flow-direction probe to indicate the instantaneous direction of a fluctuating airflow. The flow-direction generator consists of 20 small nozzles located in a rotating wheel; the nozzles are canted so that the flow direction is alternately plus and minus 10 degrees. The probe is a 3-tube assembly using two beveled tubes to sense direction and a central square-ended total-pressure tube.

Typical test data indicate that, within the dynamic pneumatic response capability of the probe, it measures transient flow direction to within  $\pm 0.5$  degrees.

An example is presented where flow turbulence measured by the 3-tube probe is compared with the measurement provided by a hot-wire anemometer.

## INTRODUCTION

It has become increasingly important, in the developmental testing of air-breathing jet engines, to make instantaneous measurements of time-varying phenomena. One of the specific research areas is inlet flow distortion and its effect on compressor stall margin. To investigate this phenomenon, total-pressure tubes with high-frequency-response elements are installed at the compressor inlet station, as well as throughout the compressor. It is also of interest to obtain the instantaneous velocity. Because velocity is a vector quantity, a measurement of the instantaneous flow direction is required, along with that of total pressure. The time variation in the static pressure, which is also required when calculating velocity, is considered small compared to the variation in total pressure.

The subject of instantaneous total-pressure measurement for the above application has been treated in references (1) and (2). The present report presents a method of obtaining the instantaneous flow direction, along with a testing device for generating known time variations in flow direction. The flow-direction probe is a

3-tube assembly using two beveled tubes to sense direction and a central square-ended total pressure tube<sup>(3)</sup>. The flow-direction generator consists of 20 small nozzles located in a rotating wheel. The nozzles are canted so that the nozzle flow direction is alternately plus and minus 10 degrees.

The approximate conditions for the experiments reported herein are: room pressure and temperature, Mach number of 0.4, flow-direction angles up to  $10^\circ$ , and frequencies up to the order of 1000 Hz. This report describes the apparatus and presents the performance of both the flow-direction measuring probe, and the nonsteady flow-direction generator.

## APPARATUS AND TESTS

### 3-Tube Probe

The 3-tube probe used in this report was designed primarily to demonstrate a technique of transient flow-direction measurement, and not intended as a working design for a particular application. The diameter of the sensing tubes had to be quite small in order to be able to test the probe in the cycling flow-direction apparatus. Such small tubing would be subject to plugging in a dirty stream. On the other hand, the miniature transducers used were those on hand, which were larger than those which would normally be used in such an application. A more desirable design would have been one in which the sensing tubes were of a diameter almost equal to the diameter of currently-available transducers (about 2 mm).

Figure 1 shows details of the 3-tube probe tested. The tip of the probe is a geometry commonly used for the measurement of total pressure and flow direction in a single plane<sup>(3)</sup>. For cases where three-dimensional flow direction is required, another set of angled tubes can be placed in a plane at right angles to that of the tubes shown in Fig. 1.

Individual miniature strain-gage type pressure transducers are placed at the ends of the sensing tubes. The sensing tubes have an inside diameter of only 0.4 mm, and particular care was used in

fabrication to insure a circular cross section in the regions of bends.

### Nonsteady Flow-Direction Generator

A photograph of the nonsteady flow-direction generator with the 3-tube probe mounted in place is shown in Fig. 2; a cross-sectional view of the main portion of the generator is shown in Fig. 3. The generator consists of a rotating wheel containing 20 nozzles, of 0.64 cm exit diameter, placed around a 6.0 cm reference diameter circle. The axial centerlines of the nozzles are canted alternately plus and minus 10 degrees in the radial direction. Thus, the stationary flow-direction probe is exposed to jets whose flow direction alternates from +10 degrees to -10 degrees.

In order to obtain the design flow direction and an adequate region of uniform flow, care had to be exercised in the shaping of the upstream bell mouths of the 20 nozzles. The flow tended to separate from that sector of the nozzles requiring divergent type flow. This problem was alleviated by enlarging the radius of curvature of the bell mouths in those sectors. After the enlargements, total-pressure surveys revealed that the flow was isentropic over 85 percent of the exit diameter on the radial centerline. This resulted in a working test section of 3.3 mm at the nozzle exits because the total-pressure losses were concentrated in the divergent portion of the nozzles. The total-pressure distributions were the same for both low (40 jets per second), and high (460 jets per second) wheel speeds.

Because of the separation problem, it was considered advisable to limit the turning angle to a maximum of 10 degrees.

It should be noted that, since the flow-direction angles lie in radial planes, the alternating flow angle is unaffected by wheel speed. The effect of centrifugal force on the jet was negligible because the radial-pressure component due to radial acceleration was less than one percent of the axial dynamic pressure.

The wheel is driven through pulleys by a variable-speed motor. Wheel speeds range up to 3000 rpm (1000 jets/sec.). The airflow supplying the jets flows through a 8.9 cm diameter duct. A small amount of leakage occurs between the end of the duct and the upstream face of the wheel due to a wheel clearance of about 0.5 mm. This leakage does not influence the performance of the wheel.

The 8.9 cm duct was also used as a free jet, with the wheel removed, with the 3-tube probe mounted in the isentropic core at the exit of the duct.

### Sequence of Tests

The tests were performed in the following sequence:

1. The steady-state sensitivity of the 3-tube probe to variation in flow direction was

determined by mounting the probe at the exit of the 8.9 cm duct (with the wheel removed) and varying the angle of attack up to  $\pm 10^\circ$ . Flow Mach numbers were 0.3 and 0.45.

2. The frequency response of the internal tubing and volume of the 3-tube probe was then determined by testing it in a sinusoidal pressure generator<sup>(4)</sup>. This generator is capable of producing sinusoidal pressures at frequencies ranging from 300 to 5000 Hz and peak amplitudes to  $0.3 \times 10^5 \text{ N/m}^2$  (0.3 atm). The generator is a resonant tube driven by an annular jet.
3. Next, the 3-tube probe was installed downstream of the wheel, and the flow characteristics of the 20 jets were determined at a low wheel speed (approx. 2 rpm). The main characteristics of interest were the flow direction issuing from the jets and the uniformity of flow from jet to jet.
4. The capability of the 3-tube probe to measure a known transient flow angle was then demonstrated by running the wheel at high speeds and relating the probe's output to the known alternating flow direction.
5. Finally, as an application, the 3-tube probe along with a hot-wire anemometer were placed in close proximity to each other in the core of a free jet of supposedly steady flow, and the indications of the two instruments compared: This test was repeated in a second jet of different size.

### Measurements and Accuracy

The primary measurements in the experiments were the pressures sensed by the 3-tube probe. These pressures were converted to voltage by the miniature pressure transducers within the probe. The voltages, which were proportional to pressure, were amplified and recorded on a multichannel FM tape recorder. The recorded data was then reproduced on an oscillograph (for low frequency data) or an oscilloscope (for high frequency data). The electrical system provided a flat frequency response of 0 to 20 kHz.

Due to the repetitive nature of the data, the signals to the oscilloscope could be recorded on an X-Y recorder, using a CRT display converter. This device converts the signals delivered to the cathode ray tube of an oscilloscope at high repetition rates (in this application up to 370 scans per second) into a low frequency scan (approximately 30 seconds per scan). Because this is a sampling technique, a high degree of CRT trace stability is required in order to yield a usable time-expanded output. In these experiments, the time-expanded traces consisted of from 500 to 10,000 samplings per trace. It is estimated that, with the above technique, the inaccuracy of flow direction measurement for the experiment was about  $1/2^\circ$ .

## RESULTS AND DISCUSSION

### Steady-State Sensitivity of 3-Tube Probe

The steady-state sensitivity of the 3-tube probe to variation in flow direction is shown in Fig. 4. The yaw angle,  $\beta$ , is plotted against yaw pressure difference  $(p_1 - p_2)/(p_{t,ind} - p_s)$ , where  $(p_1 - p_2)$  is the pressure difference of the angled tubes,  $p_{t,ind}$  is the total pressure indicated by the center tube, and  $p_s$  is stream static pressure. The denominator of the fraction is the dynamic impact pressure. The slope of the line of Fig. 4 is  $[(p_1 - p_2)/(p_{t,ind} - p_s)] = 0.047$  per degree of flow direction misalignment. This value is in agreement with other values reported in the literature<sup>(3)</sup>.

The way in which Fig. 4 is presented, with the pressure difference  $(p_1 - p_2)$  being divided by the impact pressure, is common because dividing by the impact pressure makes the results independent of velocity or Mach number. Although the data of Fig. 4 are for low Mach numbers, the results would be essentially the same for high subsonic Mach numbers. This focuses attention on an important consideration when using the 3-tube probe in a transient stream: that an instantaneous value of  $p_{t,ind}$  is required, as well as the instantaneous value of  $(p_1 - p_2)$ , in order to obtain the instantaneous flow direction. However, any time variations in the static pressure,  $p_s$ , are usually considered small. The fact that the center-tube pressure is required in order to obtain flow direction should not be considered a disadvantage. On the contrary, any study requiring the instantaneous flow direction would usually also require knowledge of the instantaneous total pressure, which is what the center tube measures.

Although the curve of Fig. 4 is for flow angles up to  $\pm 10^\circ$ , the curve is essentially linear up to  $\pm 30^\circ$ <sup>(3)</sup>. For applications where the yaw angle is greater than  $10^\circ$ , it is necessary to apply a correction to the total-pressure measurement to offset the total-pressure error associated with the yaw angle of the total-pressure tube<sup>(3)</sup>. Because of this error, it is desirable to align the 3-tube probe at the proper mean flow direction.

### Frequency Response of 3-Tube Probe

In order to interpret the readings of the 3-tube probe when used in a transient flow, the frequency response characteristics of the probe should be known. Figure 5 shows the variation in amplitude ratio and phase angle of a single tube of the probe with frequency. This information was obtained with the probe mounted in the apparatus described in reference<sup>(4)</sup>. The response predicted from elementary theory is shown along with the measured response. The agreement is within 0.5 dB up to 1900 Hz. From the figure, the measured resonant frequency is about 2000 Hz. Because it was not required, no attempt was made to obtain a particularly high resonant frequency for the

probe used in this report. For example, from the dimensions given in Fig. 1, the ratio of the cavity-to-tubing volumes was 1. Had the cavity volume been reduced to make this ratio 0.1, the resonant frequency would have increased to about 4000 Hz. The resonant frequency could also have been increased by shortening the lengths of the sensing tubing in front of the transducers. Reference<sup>(2)</sup> discusses the design criteria for obtaining higher resonant frequencies, and methods of calculating the frequency response.

An important consideration when using angled tubes to detect time-varying flow direction is that the frequency response of the angled tubes as well as the center tube should be about the same. If they are not the same, erroneous flow angles will result. Figure 6 shows examples of how drastically the response can change when the tubes become partially plugged with foreign particles. It is therefore good practice to check the response of such a probe before using it to measure transient flow angles.

### Characteristics of Nonsteady Flow-Direction Generator

The purpose of the flow generator shown in Fig. 3 and described in the Apparatus and Tests Section was to generate a high frequency alternation of flow direction. One of the basic considerations behind this type of generator is that the flow shall not be interrupted; therefore, the apparatus does not act like a siren. The undesirable effects of stopping and starting the flow through the small nozzles are also not present. The magnitude of the flow turning angle was arbitrarily chosen at plus and minus  $10^\circ$  from the axial direction. The size and number of individual nozzles was governed by the size of the 3-tube probe, and the size of the circular duct upstream of the rotating nozzles.

The 3-tube probe was used to determine the flow characteristics of the generator. This was done by locating the tip of the 3-tube probe about 0.5 mm from the downstream face of the wheel and rotating the wheel at about 2 rpm, with the flow through the nozzles at a Mach number of 0.45. Rotating the wheel slowly for the probe survey was the most convenient way to obtain the flow characteristics of the jets. Figure 7 shows some typical pressure traces as the jets moved slowly past the tip of the probe. Two simultaneous pressure traces are on the figure. The upper trace is the pressure difference  $(p_1 - p_2)$  between the two angled tubes, and the lower trace is the total pressure,  $p_{t,ind}$ , indicated by the center tube. The gain settings are such that a unit vertical distance on the  $p_{t,ind}$  trace represents twice as much pressure as a unit distance on the  $(p_1 - p_2)$  trace.

The nearly square wave shape of the traces of Fig. 7 was expected because the tip of the probe was located immediately downstream of the wheel. As the probe moves into the flow, it first passes

through a small boundary layer or mixing region, then through the flat isentropic main portion of the jet, and finally through the gradient again.

The  $p_{t,ind}$  transducer was referenced against room pressure. Because of the aspirating effect of the 20 jets, the static pressure of the jets was slightly below the pressure of the room into which the jets were flowing. As shown on the figure, the center tube pressure,  $p_{t,ind}$ , by coincidence, was indicating essentially the true static pressure of the jets when it was located between jets. When the center tube was located within the flow of the jets, it indicated a pressure which was equal to the pressure in the duct upstream of the jets. This means that the flow through the jets is isentropic since the upstream duct is essentially a plenum chamber.

The magnitude of the pressures associated with the traces of Fig. 7 can be used in conjunction with the probe sensitivity given in Fig. 4 to calculate the flow direction of the alternating jets. The result of this calculation is that the exit flow direction is  $10^\circ$  over the flat portion of the jets to within the accuracy of the experiment.

Again referring to Fig. 7, it can be seen that the flow is fairly uniform from jet to jet. Any non-uniformity is the result of the fact that the machining of all the nozzles was not identical. There are two other points of interest. First, a dip in the  $(p_1 - p_2)$  trace just before entering the  $+10^\circ$  region is evident. This is either due to lack of ability to orient the probe so that the two angle sensing tubes entered the jet flow simultaneously; or it is due to the enlarged boundary layer on one side of the nozzles, resulting from the region of divergent-type flow. Secondly, small magnitude, high-speed variations are evident in the  $(p_1 - p_2)$  trace when the probe is in the jet flow. Evidently the flow direction through each nozzle is varying slightly with time. A more dramatic example of this will be shown later in the report.

#### Response of 3-Tube Probe at High Generator Speeds

After the flow characteristics of the alternating jets were determined at a low wheel speed, the wheel was then speeded up with the probe in the same position as before. Figure 8 shows the same type of traces, but now at high wheel speeds, as were previously described. Figure 8a represents a frequency of about 50 jets per second, and Fig. 8b about 170 jets per second. These traces were obtained using the oscilloscope-CRT display converter technique described previously. This sampling technique presents an output trace representing an average over all the wheel jets over about 30 seconds. Variations in individual jets would appear in the output trace as noise. The smoothness of the traces is another indication that the flow patterns of the individual jets are the same. Figure 8a is essentially the same as the low-speed trace. Calculating the flow

direction from the trace results in a flow direction of  $10^\circ$  to within the accuracy of the experiment. At frequencies above that of Fig. 8a (50 jets per second), ringing appeared in the traces. Figure 8b shows the magnitude of the ringing for a frequency of 170 jets per second. The ringing results from the resonance of the tubing and cavity ahead of the miniature pressure transducers. As mentioned earlier, this resonance occurs at a frequency of about 2000 Hz. The ringing problem can be alleviated to some extent by electrical filtering. Figure 8c is the result of applying such a filter to the trace of Fig. 8b; the filter was a 80 dB per decade low-pass filter with a 1 kHz cutoff frequency.

Both Figs. 8b and 8c still result in a calculated flow direction of  $10^\circ$ . So, within the response capabilities of the 3-tube probe, it correctly measures both the transient flow direction and the transient total pressure. Because the probe performed satisfactorily in the high-speed generator, it may be concluded that a transient-flow-direction generator is not required to calibrate a transient-flow-direction probe. All that is really required is a steady-state flow-direction sensitivity calibration (Fig. 4), an experimental check to determine that the probe has the desired response (Fig. 5), and an assurance that the response of the two angled tubes is the same. Referring to Fig. 5 again, it can be seen that the useful frequency range of the probe is that portion of the frequency response curve for which the amplitude ratio is equal to unity (i.e., 0 dB) to within some acceptable tolerance. In cases where the damping is negligible, which is generally true of pressure probes, the upper end of the useful frequency range is approximately equal to  $\sqrt{\epsilon}$  times the resonant frequency, where  $\epsilon$  is the acceptable fractional error in pressure measurement.

#### Free-Jet Example

In the process of obtaining the steady-state flow-direction sensitivity of the 3-tube probe at the exit of the 8.9 cm duct, time varying fluctuations, greater than those normally expected, were periodically observed. Figure 9a shows a short time segment of such fluctuations for a stream Mach number of 0.3. In the figure, a linearized hot-wire anemometer trace is presented along with the  $(p_1 - p_2)$  and the  $p_{t,ind}$  traces of the 3-tube probe. The hot wire was mounted in close proximity to the 3-tube probe. The extreme left portion of the figure shows the type of traces normally expected. However, fluctuations like the large ones shown in the figure (peak values of about 10 percent) were encountered at rates ranging from one every several seconds to several a second. The intensity of turbulence during the quiet periods, as derived from the rms value of the hot-wire signal, was 0.5 percent for the above case.

Because of the way in which the hot wire was oriented in relation to the 3-tube probe, the angle portion  $(p_1 - p_2)$  of the 3-tube probe was sensitive to fluctuations normal to those of the hot wire and the center tube of the 3-tube probe. So, in

Fig. 9a, fluctuations of all three traces means that the flow is fluctuating in direction as well as magnitude. The peak values of the flow-direction and total-pressure fluctuations are also shown on the figure. Because of the high frequency of the bursts of turbulence, the 3-tube probe is "ringing"; so that any quantitative interpretation of the pressure trace is questionable. However, the values of the 3-tube probe fluctuations are approximately those expected from calculations based on the hot-wire measurements.

Figure 9b shows the same traces as Fig. 9a, except that the probes are mounted at the exit of a smaller (3.8 cm diameter) free jet. The smaller free jet resulted from clamping a 3.8 cm diameter nozzle on the exit of the 8.9 cm diameter duct. The character of the fluctuations is quite different from those of Fig. 9a. No appreciable fluctuations are indicated in the axial direction. However, fluctuations are indicated in the radial direction, and the magnitude is about half that of Fig. 9a.

The comparison of the 3-tube probe with the hot wire in a free jet is presented merely to illustrate the type of information obtainable with the 3-tube probe.

#### CONCLUDING REMARKS

A generator of nonsteady airflow direction has been developed to test the ability of a flow-direction probe to indicate the instantaneous direction of a fluctuating airflow. The flow-direction generator consists of 20 small nozzles located in a rotating wheel; the nozzles are canted so that the nozzle flow direction is alternately plus and minus 10 degrees. The probe is a 3-tube assembly using two beveled tubes to sense direction and a central square-ended total-pressure tube.

Typical test data indicate that, within the response capability of the probe, it measures the transient flow direction to within the inaccuracy of the experiment ( $\pm 0.5$  degrees), as well as transient total pressure. Because the probe performed satisfactorily in the high-speed generator, it may be concluded that the generator is not required to qualify the probe for transient application. However, the probe should be calibrated to determine the flow-direction sensitivity, and a test should also be performed to determine that the probe has the desired frequency response to accommodate a particular application.

Finally, an example is presented where flow turbulence is measured by the 3-tube probe and compared with the measurement provided by a hot-wire anemometer.

#### REFERENCES

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- (2) Nyland, T. W., Englund, D. R., and Anderson, R. C., "On the Dynamics of Short Pressure Probes: Some Design Factors Affecting Frequency Response," NASA TN D-6151, 1971.
- (3) Krause, L. N., and Dudzinski, T. J., "Flow-Direction Measurement With Fixed-Position Probes in Subsonic Flow Over a Range of Reynolds Numbers," presented at the Fifteenth National ISA Aerospace Instrumentation Symposium, Las Vegas, Nev., May 5-7, 1969.
- (4) Nyland, T. W., "Sinusoidal Pressure Generator for Testing Pressure Probes," Advances in Instrumentation, Vol. 25, Pt. 2, ISA, 1970, paper 621.

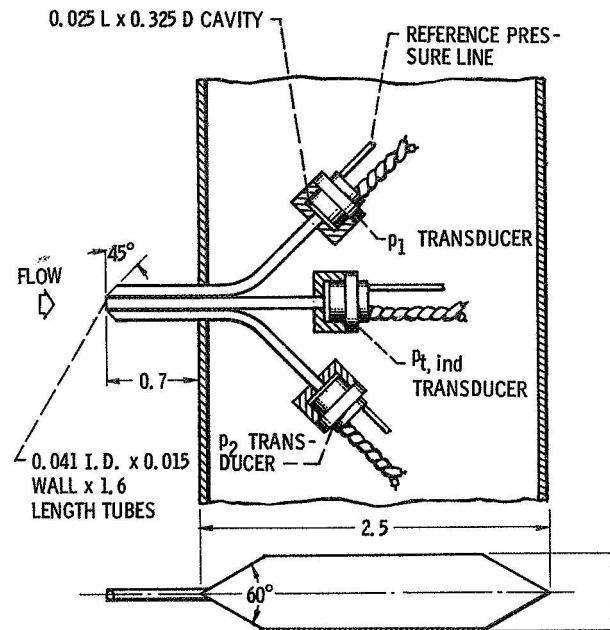


Figure 1. - Three-tube flow direction probe. Dimensions in cm.

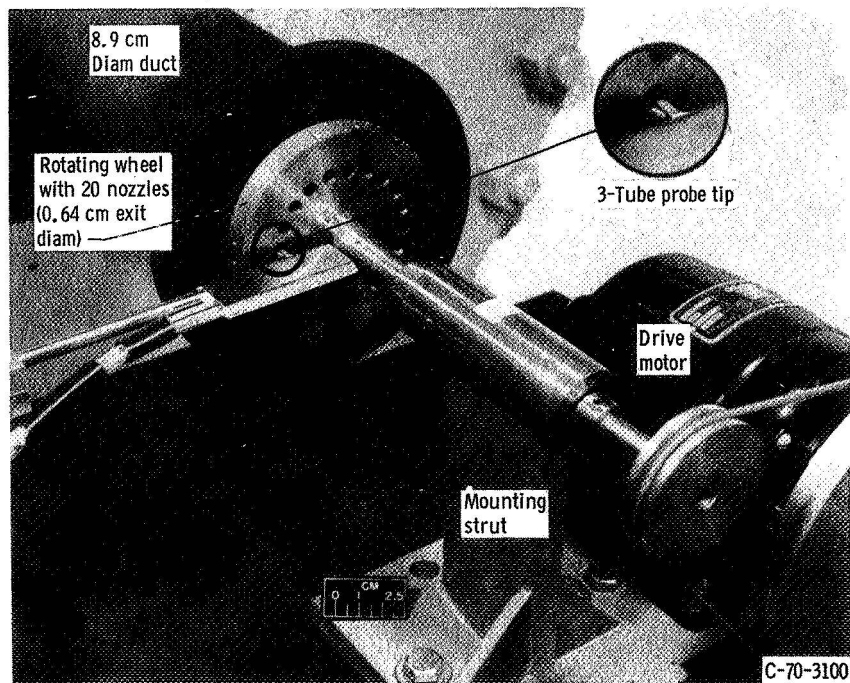


Figure 2. - Non-steady flow-direction generator with probe mounted downstream of wheel.

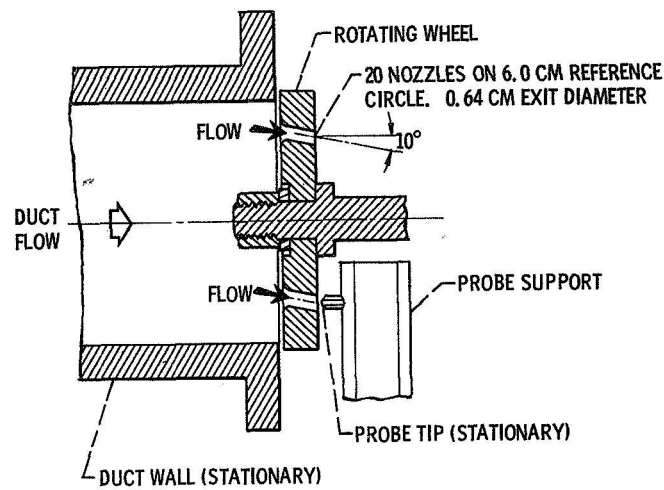


Figure 3. - Detail of non-steady flow direction generator.

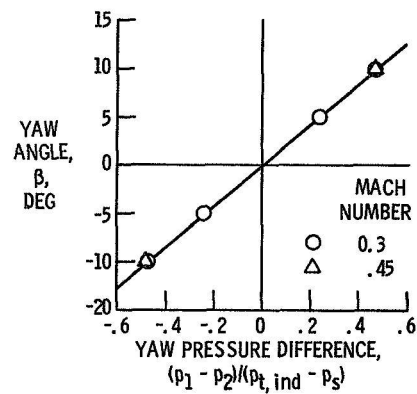


Figure 4. - Sensitivity of 3-tube probe to variation in flow direction.  $(p_1 - p_2)$  is angled-tube pressure difference.  $p_{t, ind}$  is center tube indication.  $p_s$  is stream static pressure.



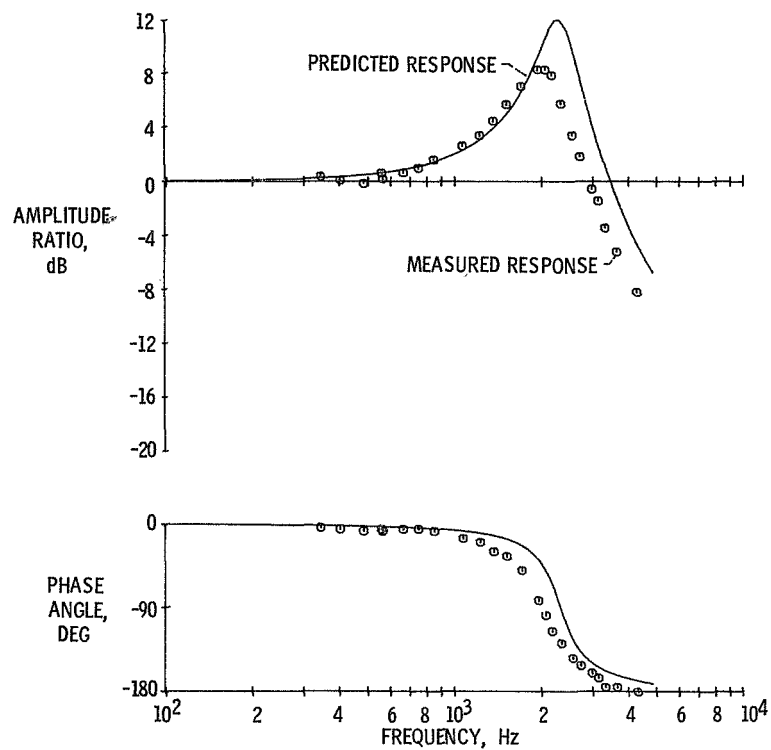


Figure 5. - Frequency response of a single tube of the 3-tube probe.

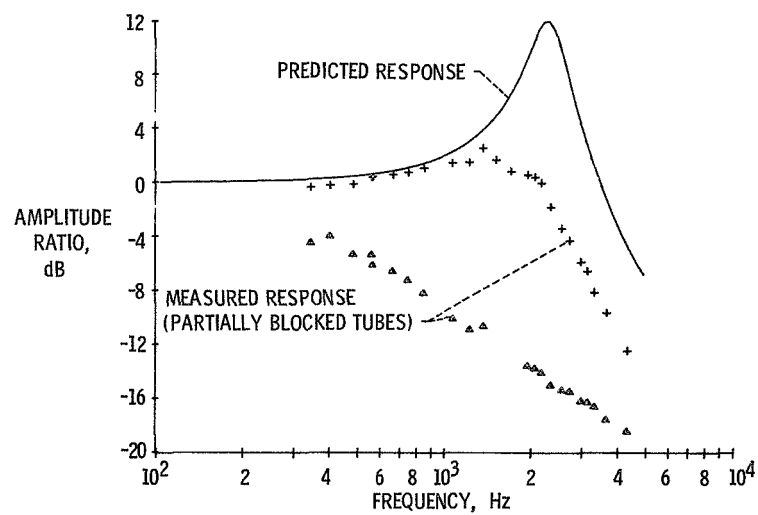


Figure 6. - Examples of frequency response of two tubes of the 3-tube probe which were partially blocked with foreign material.

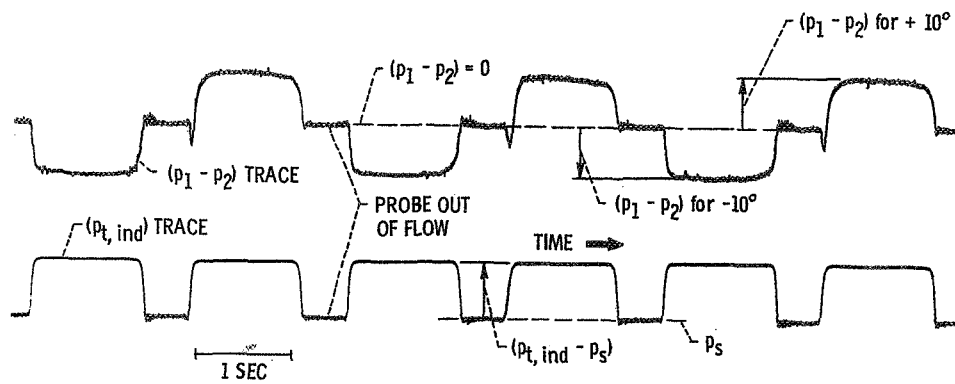
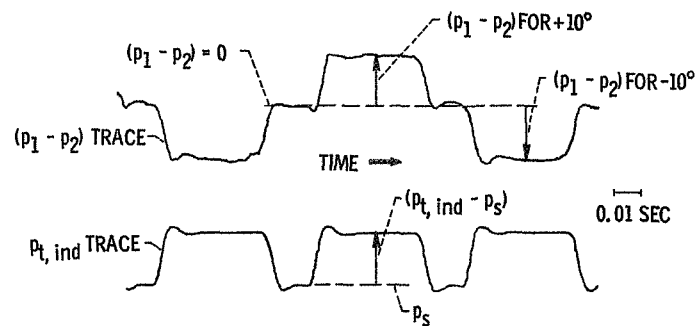
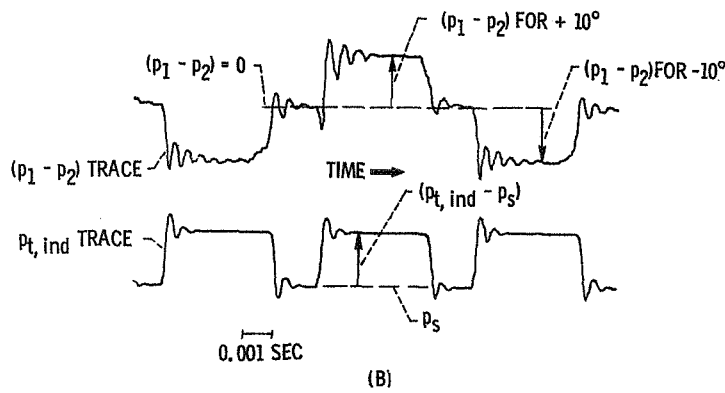
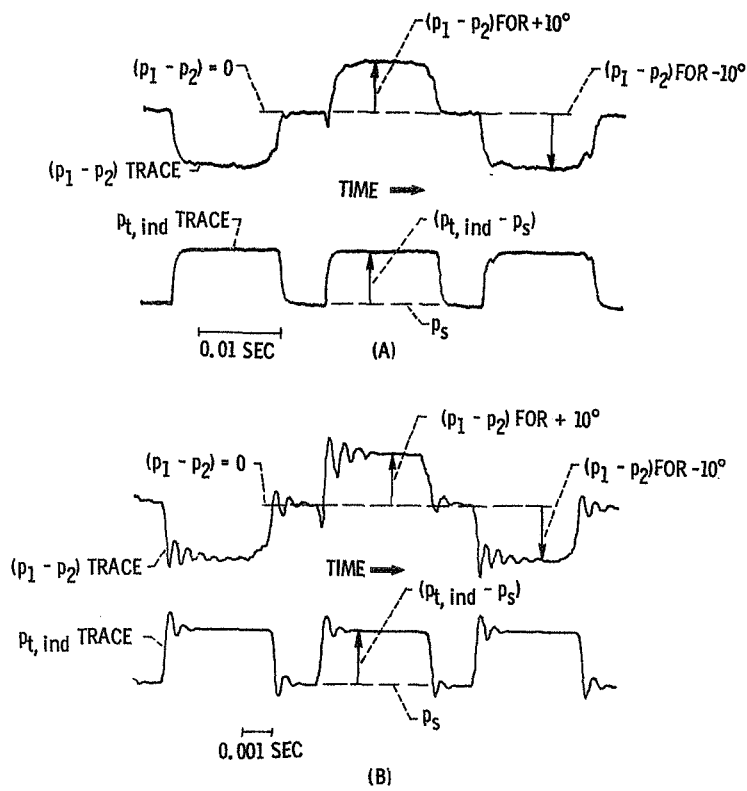
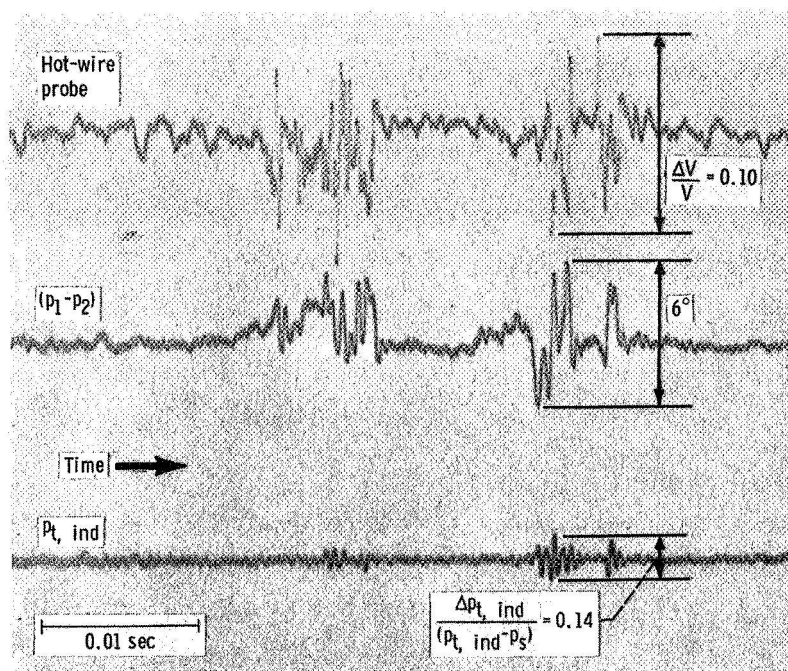


Figure 7. - Flow characteristics of the rotating jets at low rotational speed. (Real-time traces of 6 out of 20 jets).

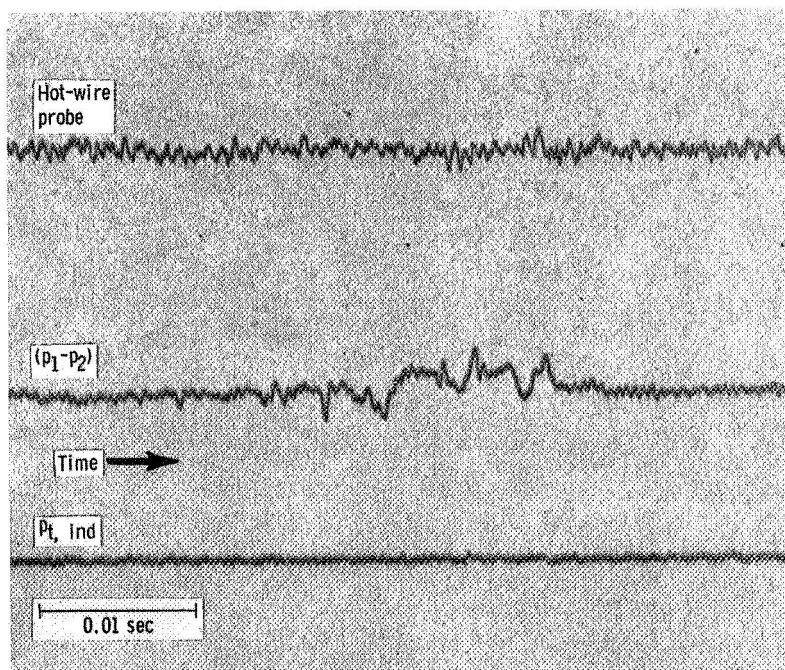


(C) SAME AS (B) BUT WITH FILTERING.

Figure 8. - Records of three-tube probe in rotating jets at high rotational speeds. (Traces represent the average of all jets over 30 seconds.)



(a) 8.9 cm Diam free jet.



(b) 3.8 cm Diam free jet.

Figure 9. - Records of the 3-tube probe and a hot-wire probe in two free jets.